LLNL-JRNL-654961

LAWRENCE LIVERMORE NATIONAL LABORATORY

ABL and BAM Friction Analysis Comparison

K. F. Warner, D. L. Remmers, G. W. Brown, M. M. Sandstrom, J. J. Phillips, T. J. Shelley, J. A. Reyes, P. C. Hsu, J. G. Reynolds

May 28, 2014

Propellants Explosives and Pyrotechnics Journal

Disclaimer

Propellants,
Explosives,
Pyrotechnics

Full Paper

DOI: 10.1002/prep.201((full DOI will be filled in by the editorial staff))

ABL and BAM Friction Analysis Comparison

Kirstin F. Warner,[a] Mary M. Sandstrom,[b] Geoffrey W. Brown, [b] Daniel L. Remmers,[a] Jason J. Phillips,[c] Timothy J. Shelley,[d] Jose A. Reyes,[e] Peter C. Hsu,[f] and John G. Reynolds*[f]

Abstract: The Integrated Data Collection Analysis (IDCA) program has conducted a proficiency study for Small-Scale Safety and Thermal (SSST) testing of homemade explosives (HMEs). Described here is a comparison of the Alleghany Ballistic Laboratory (ABL) friction data and Bundesanstalt für Materialforschung und -prüfung (BAM) friction data for 19 HME and military standard explosives. Two methods were employed to reduce the data—modified Bruceton analysis (F_{50}) and the threshold initiation level analysis (TIL). The study provides a full list of friction sensitivity data for the 19 materials by both ABL and BAM friction testing equipment.

Specific results highlight the differences more than the similarities of the two methods. PETN and $KClO_3$/sugar mixtures exhibit the most sensitivity of the materials studied by both testing methods. On the other hand, H_2O_2/fuel mixtures exhibit no sensitivity in ABL testing, but exhibit some sensitivity in BAM testing. For the UNi mixtures, the behavior was the opposite, no sensitivity in BAM but some sensitivity in ABL. $KClO_4$/Al mixtures exhibit high sensitivity in the ABL method, but only moderate sensitivity in the BAM method. Other differences are seen in the relative sensitivities underscoring the differences in the mechanisms of how each test method operates. In some cases, data could not be attained because of the physical nature of the material. Comparison between the two friction methods on a material-by-material basis using absolute values not surprisingly yielded essentially no systematic correlations. Even the relative order showed little correlation between the two methods.

The Department of Homeland Security (DHS) funded this effort. Each participating testing laboratory uses identical test materials and preparation methods. However, the test procedures differ among the laboratories. The testing performers involved are Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Naval Surface Warfare Center, Indian Head Division Explosive Ordnance Disposal Technology (NSWC IHEODTD), Sandia National Laboratories (SNL), and Air Force Research Laboratory (AFRL/RXQL).

Keywords: Small-scale safety testing, proficiency test, friction, round-robin test, safety testing protocols, HME, ABL friction, BAM friction

1 Introduction

Exposure of an energetic material to friction forces can cause hot spots that can lead towards reactions [1-4]. Therefore, determining friction sensitivity is a critical exercise in developing safe handling practices of energetic materials. Several tests have been designed for determining friction sensitivity [5], and two of the more commonly used tests are the BAM and the ABL Friction test.

The BAM method was developed around 1955 by German Bundesanstalt für Materialforschung und -prüfung testing laboratory. The method uses a ceramic pin and plate with a CAM drive to produce the friction motion. This method corresponds to the UN Recommendations on the Transport of Dangerous Goods, 13.5 Test 3(b) (i), STANAG 4487, the Official Journal of the European Community as well as to the Directive 84/449/EEC and NF T 20-038 Test A.14 [6].

The ABL method was developed around 1960 by the Allegany Ballistics Laboratory. The method uses a striker wheel against a flat anvil to produce the friction motion. This method has a similarity of the U. S, Bureau of Mines pendulum friction machine of the early 1900s that used a weight on a pendulum to

[a] K. F. Warner, D. L. Remmers
Naval Surface Warfare Center, Indian Head Explosive Ordnance Disposal Technology Division (IHEODTD),
Indian Head, Maryland (USA)
[b] G. W. Brown, M. M. Sandstrom,
Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico (USA)
[c] J. J. Phillips
Sandia National Laboratories,
Albuquerque, New Mexico (USA)
[d] T. J. Shelley
Bureau of Alcohol, Tobacco & Firearms,
Redstone Arsenal, Alabama (USA)
[e] Jose A. Reyes
Applied Research Associates,
Tyndall Air Force Base, Florida (USA)
[f] P. C. Hsu, J. G. Reynolds
Lawrence Livermore National Laboratory,
Livermore, California (USA)
*e-mail: reynolds3@llnl.gov

cause the surfaces to slip. Although not as widely used, the ABL method is gaining popularity, particularly in the U. S., as a valid method to measure friction sensitivity. The ABL Friction test is also cited in "Recommendation on the transport of Dangerous Goods: Tests and Criteria, Second Edition," by the UN as one of the tests used to determine if a material is too dangerous to transport [7].

These two test methods use completely different approaches to simulate friction in process conditions. Even the results are recorded in different units—BAM method, newtons (or kg); ABL method, MPa (psig)/at a specified pendulum velocity. Because of this, the results of the two methods do not seem readily comparable. A method or relationship to do so would be desirable. There have been efforts in the literature to develop a translation function among friction testing methods [8,9]. However, as far as the authors can find, no attempt has been made to correlate ABL and BAM friction testing results.

The Integrated Data Collection Analysis Program (IDCA) is a group of explosives testing laboratories that have worked together to adapt small-scale safety and thermal (SSST) testing to homemade explosives (HMEs). Chartered under the Department of Homeland Security (DHS), the IDCA conducted a proficiency, or round robin type test of 19 materials. The IDCA proficiency test was designed to assist the explosives community in comparing and perhaps standardizing inter-laboratory SSST testing for HMEs and aligning these procedures with comparable testing for typical military explosives [10]. The materials for the proficiency test have been selected because their properties invoke challenging experimental issues when testing HMEs. Many of these challenges are not normally encountered with military type explosives. To a large extent, the issues are centered on the physical forms and stability of the improvised materials.

As an added benefit of the proficiency test, the Naval Surface Warfare Center, Indian Head (IHEODTD) has both BAM and ABL friction testing equipment. At that laboratory, all the materials in the proficiency test were examined by both methods under essential identical environmental conditions. This provides the opportunity to examine and compare the results of both methods, and to try to find a translation function between the results from both methods. If this translation function is possible, then friction sensitivity assessment by one method could possibly be used by the other method, therefore decreasing the amount of testing needed for a specific material, and allow sensitivity results from one laboratory be considered by another laboratory.

The subject of this paper is the behavior of the 19 HME and military materials examined by ABL and BAM friction testing equipment. The lead testing performer in this work is Naval Surface Warfare Center, Indian Head Explosive Ordnance Disposal Technology Division (NSWC IHEODTD), with contribution testing performers of Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and Tyndall Air Force Research Laboratory (AFRL).

2 Experimental Section

2.1 Materials

The sources of the materials in Table 1 have been discussed previously [10]. All samples were prepared according to IDCA drying and mixing procedures [11,12]. Briefly, powders were dried in an oven at 60°C for 16 h, then cooled and stored in a desiccator until use.

Table 1. Materials for IDCA Proficiency Study

Material[a]	ID	Form[b]
$KClO_4$/Al	$KClO_4$/Al	Dry powder
$KClO_4$/C[c]	$KClO_4$/C	Dry powder
$KClO_4$/dodecane	$KClO_4$/D	Wet powder
$KClO_3$/dodecane	$KClO_3$/D	Wet powder
$KClO_3$/sugar[d]	$KClO_3$/Sg 100	Dry powder
$KClO_3$/sugar[e]	$KClO_3$/Sg AR	Dry powder
$NaClO_3$/sugar[d]	$NaClO_3$/Sg	Dry powder
AN[f]	AN	White powder
Bullseye® gunpowder	GP	Black powder
AN/Bullseye® gunpowder	AN/GP	Gray powder
UNi/Al[g]	UNi/Al	Dry powder
UNi/Al/S	UNi/Al/S_8	Dry powder
H_2O_2/cumin[h,i]	H_2O_2/Cmn	Viscous paste
H_2O_2/nitromethane[j]	H_2O_2/NM	Miscible liquid
H_2O_2/flour[h,k]	H_2O_2/Fl	Sticky paste
H_2O_2/glycerol[h]	H_2O_2/Gl	Miscible liquid
HMX Grade B	HMX	Powder
RDX Type II Class 5[l]	RDX	Powder
PETN Class 4[l]	PETN	Powder

[a] Mixture or pure material, [b] observed physical form, [c] activated charcoal (Darco), [d] $KClO_3$ used is -100 mesh, [e] $KClO_3$ used is as received, [f] ammonium nitrate, [g] Urea nitrate, [h] 70% H_2O_2, [i] *cuminum cyminum*, [j] 90% H_2O_2, [k] chapatti, [l] standard

2.2 Data analyses

The raw friction data set is far too big for presentation in this document. This data is available directly from the corresponding author. The data presented here is in the reduced form by a modified Bruceton analysis [13] and a threshold initiation level (TIL) analysis [14]. These methods have been discussed in detail previously [15].

3 Results

The HMEs were tested with the two different friction methods in an effort to: 1) accumulate friction sensitivity data by two common friction test methods, and 2) possibly develop a translation between the two testing methods.

3.1 ABL Friction Testing

Figure 1 shows the ABL friction testing equipment. ABL friction testing system uses a steel wheel sliding 1" across the sample on a steel plate. The pressure between the wheel and plate is varied, using 13 levels between 0.31 MPa (30 psig) and 7.0 MPa (1000 psig). The speed of the plate can be varied from 31 cm/sec to 244 cm/sec. The sample size is 35-45 mg per trial. The sensitivity ranges are determined as follows: 0.31 MPa (30 psig) or less is considered

High; 0.38 to 3.0 MPa (40-420 psig) is considered medium; and 4.0 to 7.0 MPa (560-1000 psig) is considered low. The sensitivity is reported in MPa (psig) at a specified plate velocity. The initiation of the sample is determined by the production of smoke, fire, pop, or flash. For this study, the ABL data was performed at 244 cm/s, the F_{50} data was determined by the modified Bruceton Method [13], and the threshold initiation level (TIL) [14] is the level at which 20 negatives are observed with at least one positive at the next higher level. The F_{50} data is the 50% initiation level where the samples will exhibit reaction.

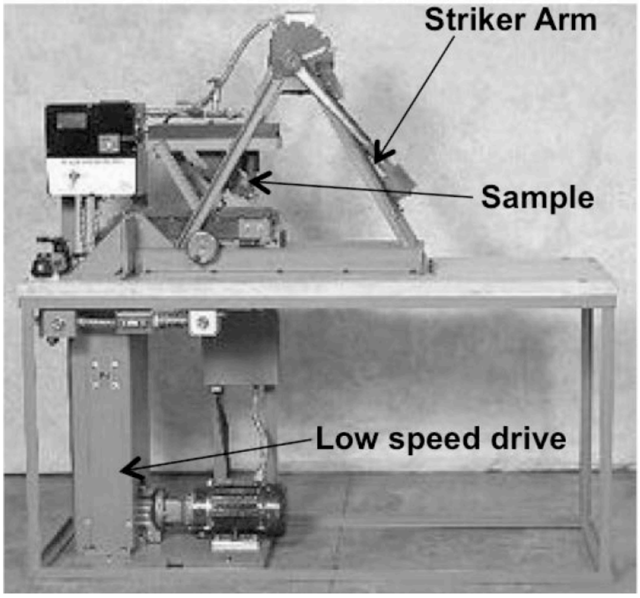

Figure 1. ABL Friction Equipment (picture courtesy of Safety Management Services www.sms-ink.com)

3.2 BAM Friction Testing

Figure 2 shows the BAM friction testing equipment, which is the NATO standard friction test. It uses a porcelain peg sliding back and forth 1 cm across the sample on a porcelain plate. The force between the peg and plate is varied between 6 and 360 newtons. The sample size is 35-45 mg per trial. The sensitivity ranges are determined as follows: 6-54 N is considered high; 60-144 N is considered medium; and 160-360 N is considered low. The sensitivity is reported in newtons. However, the sensitivity can be reported in kg, also. The initiation of the sample is determined by the production of smoke, fire, pop, or flash. Both the Bruceton and TIL methods are used for data reduction. The TIL here is the level at which 10 negatives are observed with at least one positive at the next higher level. .

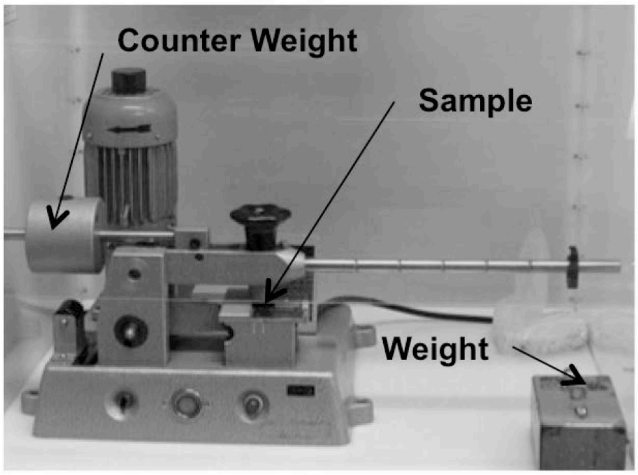

Figure 2. BAM Friction Testing Equipment

Table 2. Operational parameters of ABL and BAM Friction test equipment

ABL Friction	BAM Friction
Tooling Criteria • Dimensions: Specified minimum/maximum • Material: Latrobe "MGR" Tool-Steel Alloy (ASTM A8) • Hardness: R_c 58-62 • Roughness: 50 - 70 m-in (1.270 - 1.778 mm) • Lay: Perpendicular to direction of Anvil travel	**Tooling Criteria** • Dimensions: As supplied by single-source Vendor. No acceptance-testing. • Material: Ceramic (porcelain; peg color has changed from white to grey). • Hardness: 5-6 (Mohs) • Roughness: 2 μm • Lay: Perpendicular to direction of Plate travel.
Sliding Velocities • 0 - 305 cm-sec^{-1}; High (impact) and Low (mechanical) drives calibrated • Selectable (244 cm-sec^{-1} for these DHS characterizations)	**Sliding Velocities** • Sinusoidal (sweep; not constant-velocity) • Not selectable; Invariant range (Scotch Yoke-driven) • Exact velocity at which reaction occurs is unclear
Normal Force • Selectable; applied by calibrated hydraulic system • Definite "nip" applied to material	**Normal Force** • Selectable; applied by weight and beam • Definite "plow-like" behavior
Test Protocols • Each shot must use a new surface on the Anvil and on the Wheel • Stroke: One-inch (25.4 mm) required	**Test Protocols** • Each shot must use a new surface on the Plate and Peg • Stroke: 10 mm
Data Reduction • Can construct Friction Maps (ex. 20-TILs), Probits • Real-world engineering terms (margins, probabilities) extracted	**Data Reduction** • Hierarchical ranking of sensitivities • Measured data are laboratory results

The architectural designs of ABL and BAM systems are vastly different and hence the response to the various HMEs is different. The ABL is more like a "nip" and BAM is more "plow like". Table 2 compares the operational parameters of the two methods, accentuating the differences in the mechanisms by which the friction insults are applied.

Figure 3 diagrams differences in the mechanics of the two test methods. The ABL method has only hardened steel surfaces, while the BAM method uses porous ceramics. The insult point for the ABL method is a nipped or pinched area between two non-porous steel surfaces, while for the BAM method, the sample is plowed over a porous surface with the use of a ceramic peg. In both cases, the support surface moves, but this motion is different in the two cases. It is also important to remember that the ABL applies force using pressure-regulated action and BAM applies force using weight regulated action, so the response levels are in MPa (psig) and N (kg), respectively.

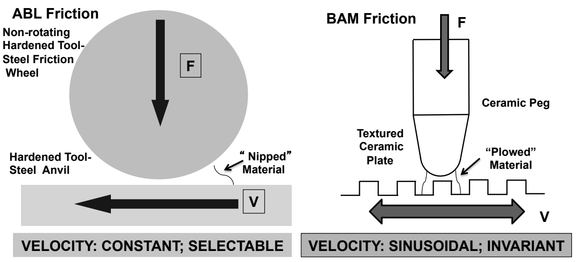

Figure 3. Diagrams of ABL and BAM friction action during testing

3.3 Friction Testing Data

All materials in Table 1 were tested on ABL and BAM equipment for the 50% probability of reaction (F_{50}) and TIL. Table 3 lists the average data for both data reduction methods. The method for determining the average has been delineated previously [10].

Table 3. F_{50} and TIL values by ABL and BAM Friction Methods

Material	ABL TIL, MPa; F_{50}, MPa	BAM TIL, N; F_{50}, N
$KClO_4$/Al	< 0.31; 0.45	161.8; 262.8
$KClO_4$/C	0.87; 2.04	> 360; ND
$KClO_4$/D	2.51; 5.04	323.6; > 360
$KClO_3$/D	1.03; 3.53	161.8; 262.8
$KClO_3$/Sg 100	0.31; 0.39	22.6; 43.1
$KClO_3$/Sg AR	0.95; 1.14	31.4; 35.3
$NaClO_3$/Sg	1.65; 3.18	43.1; 154.9
AN	2.76; ND	360; > 360
GP	ND; 2.28	136.3; > 360
AN/GP	1.63; 1.20	119.6; 124.5
UNi/Al	1.60; 3.93	> 360; ND
UNi/Al/S	1.60; 2.69	> 360; ND
H_2O_2/Cmn	> 7.0; ND	84.3; 109.8
H_2O_2/NM	> 7.0; ND	> 360; ND
H_2O_2/Fl	> 7.0; ND	111.8; ND
H_2O_2/Gl	> 7.0; ND	115.7; 171.6
HMX	0.41; 0.87	84.3; 138.3
RDX Set 1	0.48; 1.07	148.1; ND
RDX Set 2	0.74; 1.53	115.7; 272.6
RDX Set 3	0.74; 0.95	111.8; 189.3
RDX Set 4	0.62; 1.20	115.7; 171.6
PETN	0.15; 0.39	42.2; 67.7

7.0 MPa (1000 psig) is upper limit for ABL method; 360 N (36.7 kg) is upper limit for BAM method

The differences in design of the two methods are evident in some of the materials. For example, the H_2O_2/fuel mixtures exhibit no sensitivity in the ABL method, but have various level of sensitivity by the BAM method. The UNi mixtures show the opposite trend exhibiting no sensitivity by the BAM method but reasonable sensitivity by the ABL method.

Table 4. Relative order of friction sensitivity based on F_{50} or TIL for ABL and BAM methods

Order ABL TIL	Order BAM TIL	Order ABL F_{50}	Order BAM F_{50}
PETN >	$KClO_3$/Sg 100 >	$KClO_3$/Sg 100 =	$KClO_3$/Sg AR >
$KClO_4$/Al >	$KClO_3$/Sg AR >	PETN >	$KClO_3$/Sg 100 >
$KClO_3$/Sg 100 >	PETN >	$KClO_4$/Al >	PETN >
HMX >	$NaClO_3$/Sg >	HMX >	H_2O_2/Cumin >
RDX Set 1 >	H_2O_2/Cumin >	RDX Set 3 >	AN/GP >
RDX Set 4 >	HMX >	RDX Set 1 >	HMX >
AN/GP >	RDX Set 3 =	$KClO_3$/Sg AR >	$NaClO_3$/S >
RDX Set 2 =	H_2O_2/Flour >	AN/GP >	H_2O_2/Gl =
RDX Set 3 >	H_2O_2/Glycerol =	RDX Set 4 >	RDX Set 4 >
$KClO_4$/C >	RDX Set 2 =	RDX Set 2 >	RDX Set 3 >
$KClO_3$/Sg AR >	RDX Set 4 >	$KClO_4$/C >	$KClO_3$/D =
$KClO_3$/D >	AN/GP >	GP >	$KClO_4$/Al >
UNi/Al =	GP >	UNi/Al/S >	RDX Set 2 >
UNi/Al/S >	RDX Set 1 >	AN >	AN ND
$NaClO_3$/Sg >	$KClO_4$/Al =	$NaClO_3$/Sg >	GP ND
$KClO_4$/D >	$KClO_3$/D >	$KClO_3$/D >	$KClO_4$/C ND
AN>	$KClO_4$/D >	UNi/Al >	$KClO_4$/D ND
H_2O_2/Cmn ND	$KClO_4$/C ND	$KClO_4$/D >	UNi/Al ND
H_2O_2/NM ND	AN ND	H_2O_2/Cmn ND	UNi/Al/S ND
H_2O_2/Fl ND	UNi/Al ND	H_2O_2/NM ND	[H_2O_2/NM]
H_2O_2/Gl ND	UNi/Al/S ND	H_2O_2/Fl ND	[H_2O_2/Fl]
[GP]	H_2O_2/NM ND	H_2O_2/Gl ND	[RDX Set 1]

> = more sensitive than material below in table; = = equal sensitivity to the material below in the table; ND = above the highest setting of the equipment; in brackets, [] was not tested

A better indicator of the differences and similarities of the two methods is seen in the relative sensitivities. Table 4 shows the relative sensitivity of the materials based on the method used for measuring sensitivity and the method used for ranking the sensitivity.

For all the determinations, ABL TIL and F_{50} and BAM TIL and F_{50}, $KClO_3$/Sg and PETN are generally on the top of the list for friction sensitivity. HMX is rated relatively less, but still near the top of the list for sensitivity. On the opposite end of the sensitivity scale, UNi mixtures tend to exhibit little or no friction sensitivity for all the methods.

Many of the other materials exhibit one type of behavior for one method, and the opposite behavior for the other method. Examples of these are $KClO_4$/Al, $KClO_4$/C, and $NaClO_3$/Sg.

Liquids and pastes tend to be less sensitive on the ABL method compared to the BAM with exception of H_2O_2/NM mixture. This could be attributed to the miscibility of nitromethane in hydrogen peroxide.

The military grade explosives (RDX, PETN and HMX) showed consistent sensitivity data trends, in most cases, between the two methods. RDX and HMX showed medium sensitivity on both ABL and BAM testers. PETN showed high sensitivity on both testers. This could be attributed to the mono-molecular nature of the samples.

3.4 Correlations between ABL and BAM Methods

In attempt to determine if there is a direct correlation between the two methods the TIL data for the materials are shown in Figure 4 and for the F_{50} data in Figure 5. In both figures, the x-axis represents the ABL data values, and the y-axis represents the corresponding BAM data values.

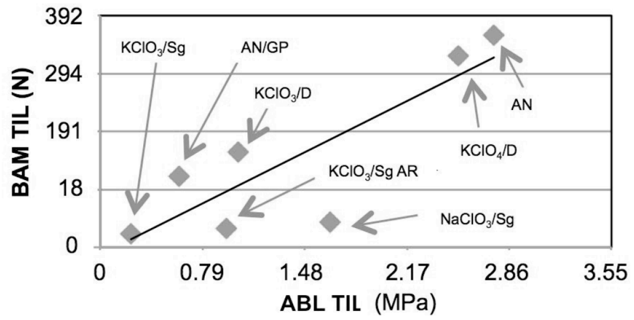

Figure 4. Friction sensitivity by TIL assessment by the ABL (x-axis) and the BAM (y-axis) methods

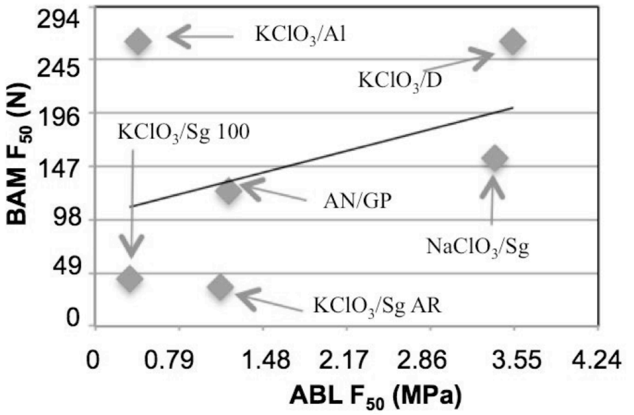

Figure 5. Friction sensitivity by F_{50} assessment by ABL (x-axis) and the BAM (y-axis) methods

Clearly there is no correlation of the data between the two testing methods. Dividing the data into sub-groups does not provide any correlations either (HMEs, TIL R^2 = 0.5372, F_{50} R^2 = 0.16708). The lines in the figures are the linear fits to the data.

4 Discussion

4.1 Comparison with Proficiency Test Result

These results were taken directly from the proficiency test. IHEODTD is the only performer in that test that has both the ABL and BAM friction equipment. However, the other participants had either the BAM equipment or the ABL equipment. LLNL and LANL produced full data sets on the BAM friction results on the same suite of materials. These results have been presented elsewhere [10], but a brief comparison is warranted here.

In general, the order of relative sensitivity derived for LLNL and LANL are about the same as for IHEODTD for F_{50} and, to a lesser extent, the TIL determinations. The most sensitive materials of the suite are $KClO_3$/Sg mixtures and PETN. The least sensitive (no detected sensitivity) are the UNi/Al, UNi/Al/S mixtures, some of the H_2O_2/fuel mixtures, AN and $KClO_4$/C. The rest of the materials are in various, but similar orders. The contrasting results are that IHEODTD found sensitivity in some of the liquid H_2O_2/fuel mixtures, while LLNL and LANL did not. Also, from an absolute perspective, IHEODTD and LANL results are generally closer than the corresponding results from LLNL. This has been assigned to the testing environment [10,15].

RDX was used as a standard and was tested several times in the proficiency test. Enough data were collected to examine the results from statistical models. From this study, a range of expected results for friction sensitivity was derived for F_{50} data analysis for RDX. The expected range is defined in this case as the expected value or values of a measurement done on the same batch of RDX by any laboratory and was found to be 205.9 N (21.0 kg) with a variability of 40% [15].

This variability concept can be applied to the other materials studied in the proficiency test to see if results agree. However, in those cases, not enough data were taken to perform direct statistical analyses as in the RDX study. To provide an average value and a variability for each material, the variability derived for RDX study can be applied to the materials of this study to calculate whether the values derived from each participant agree based on an expected range of observation.

Eight materials met the criteria for the F_{50} determinations for BAM friction measurements (ABL measurements were only performed by IHEODTD) to apply this variability—full data sets measured by IHEODTD and at least one other participant. All the values fall into the expected range of results based on the variability determined by the RDX statistics except for one material, $KClO_3$/Sg AR, which was slightly out of the expected range of results.

This finding is interesting because, for BAM friction testing, LLNL consistently reports more stable friction sensitivity than the corresponding values from the other participants. This behavior has been assigned to the local environment of the BAM equipment at LLNL being significantly different than LANL or IHEODTD because the equipment itself is from the same design. The fact that the materials in this study also fall within the variability range predicted by the RDX study is not surprising because the variability from the RDX study included LLNL determined BAM results. This finding suggests to develop more narrow variability, even tighter controls on the configuration of the equipment is necessary, something that was not done in the proficiency test. It also affirms that the statistics determined by the RDX study apply to different materials, and that statistical studies on each of the materials are not necessary. Perhaps it is more important to further standardize and calibrate equipment than to measure excessive repeats of the same material to get a narrower variability.

4.2 Results Linked to Friction Test Method

In comparing the friction sensitivities of selected materials measured by the two methods, BAM and ABL, some phenomenological relationships can be used to highlight differences in the two methods. These causalities are not to be taken as a rigorous scientific examination, but to simply understand the limitations of each technique in regard to friction testing of new materials (such as HMEs) and what the results really mean. These friction-testing methods derive validation on traditional energetic materials and the insult mechanism is generally thought to be the same for all the materials. However, the insult mechanism may be different when HMEs are examined because of the diverse nature of the material composition of HMEs, so care must be taken to understand the results relative to what is being tested.

Liquids. In the ABL method, the liquids almost exclusively show no sensitivity, while for the BAM method, some show moderate sensitivity. In the ABL method, the material is insulted between the steel wheel and a steel anvil in a "nipped" action on hardened steel surfaces, while for BAM, the material is insulted in a "plow" wave front on porous ceramic surfaces. Likely the ABL insult is somewhat mitigated by the lubricating effect on the non-porous steel surfaces by the liquid, more than the porous surface sites.

Al containing materials. Al mixtures tend to show more sensitivity with the ABL method than the BAM method. For example, UNi/Al mixtures show no sensitivity by the BAM method while modest sensitivity by the ABL method. The nip mechanism of ABL could expose fresh Al surface better than the plow mechanism of BAM, therefore producing more hot spots for non-shock initiated reactions.

Non-sensitive materials. Of the HMEs tested, the BAM method had more non-sensitive readings than the ABL method. In this type of testing, non-shock hot-spot sites are very important to initiate reactions. This topic has been discussed for years and a simplest interpretation is that the harder the material, the better chance for forming hot-spot, although other condition must be considered. In these two testing methods, the steel is definitely harder than porcelain, so the material hardness could be a factor.

5 Conclusions

The architecture of the ABL and BAM friction test methods is vastly different. As a result, a correlation between results on the same suite of materials could not be attained. However, samples that were uniform or miscible, similar results were obtained by both methods. In addition, wide ranges of materials were tested and the results presented here. Even though there is not much of a correlation, these results can still be used empirically.

Acknowledgments

The authors thank Doug Bauer, Laura J. Parker and Greg Struba for their enthusiastic support; Bob Ford of SMS-Ink for ABL friction test equipment picture. This work was performed by the Integrated Data Collection Analysis (IDCA) Program, a five-lab effort supported by Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, the Air Force Research Laboratory, and Indian Head Division, Naval Surface Warfare under sponsorship of the U.S. Department of Homeland Security, Science and Technology Directorate, Explosives Division. Los Alamos National Laboratory is operated by Los Alamos National Security, LLC, for the U.S. Department of Energy under Contract DE-AC52-06NA25396. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The Air Force Research Laboratory and Indian Head Division, Naval Surface Warfare also performed work in support of this effort under contract HSHQDC10X00414. LLNL-JRNL-654961 (775550).

References

[1] F. P. Bowden and O. A. Gurton, Initiation of Explosions by Grit Particles, *Nature*, **1948**, *162*, 654-655.

[2] F. P. Bowden and O. A. Gurton, Initiation of Solid Explosives by Impact and Friction: The Influence of Grit, *Proc. R. Soc. Lond. A* **1949** *198* (1054) 337-349.

[3] A. S. Dyer and J. W. Taylor, Initiation of Detonation by Friction on a High Explosive Charge, *5th Symposium (International) on Detonation*, August 18-21, 1970, Pasadena CA, *ONR,* **1970**, *ACR-184*, 291-300.

[4] J. E. Field, K. N. Bourne, S. J. P. Palmer, and S. M. Walley, Hot-Spot ignition mechanisms for explosives and propellants, *Phil. Trans. R. Soc. Lond*. **1992**, *A 339*, 269-283.

[5] B. Hill, Sensitivity Testing History Overview, *SMS Explosives Testing Users Group Annual Meeting,* **2012**, Park City UT, October 22.

[6] R & P Material Testing Instruction Manual for BAM Friction Tester, Reichel & Partner, GmbH, Rheinzabern, Germany.

[7] ABL Friction Sensitivity Tester Operating Procedure, Explosives Testing User's Group Standards, 10/26/2010 (available at http://www.etusersgroup.org).

[8] R. K. Wharton and J. A. Harding, An Experimental Comparison of Three Documented Test Methods for the Evaluation of Friction Sensitivity, *J. Energetic Materials*, **1993**, *11*, 51-65.

[9] R. K. Wharton and D. Chapman, The Relationship between BAM friction and Rotary Friction Sensitiveness Data for High Explosives, *Propellants, Explos. Pyrotech.*, **1997**, *22*, 71-73.

[10] M. M. Sandstrom, G. W. Brown, D. N. Preston, C. J. Pollard, K. F. Warner, D. N. Sorensen, D. L. Remmers, J. J. Phillips, T. J. Shelley, J. A. Reyes, P. C. Hsu and J. G. Reynolds, Variation in Methods in Small-Scale Safety and Thermal Testing of Improvised Explosives, *Propellants Explos. Pyrotech*., **2014**, accepted for publication.

[11] B. D. Olinger, M. M. Sandstrom, K. F. Warner, D. N. Sorensen, D. L. Remmers, J. S. Moran, T. J. Shelley, L. L. Whinnery, P. C. Hsu, R. E. Whipple, M. Kashgarian, and J. G. Reynolds, *Integrated Data Collection Analysis (IDCA)*

Program—Mixing Procedures and Materials Compatibility, IDCA Program Analysis Report *002*, LLNL-TR-422028, **2009,** December 27 (available through Lawrence Livermore National Laboratory Technical Information System).

[12] B. D. Olinger, M. M. Sandstrom, G. W. Brown, K. F. Warner, D. N. Sorensen, D. L. Remmers, J. S. Moran, T. J. Shelley, L. L. Whinnery, P. C. Hsu, R. E. Whipple, and J. G. Reynolds, *Integrated Data Collection Analysis (IDCA) Program—Drying Procedures,* IDCA Program Analysis Report *004*, LLNL-TR-465872, **2010**, April 27 (available through Lawrence Livermore National Laboratory Technical Information System).

[13] W. J. Dixon and A.M. Mood, A Method for Obtaining and Analyzing Sensitivity Data, *J. Am. Stat. Assoc.,* **1948,** 43, 109-126.

[14] Department of Defense Ammunition and Explosives Hazard Classification Procedures, TB 700-2 NAVSEAINST 8020.8B TO 11A-1-47 DLAR 8220.1, **1998**, January 5.

[15] G. W. Brown, M. M. Sandstrom, D. N. Preston, C. J. Pollard, K. F. Warner, D. N. Sorensen, D. L. Remmers, J. J. Phillips, T. J. Shelley, J. A. Reyes, P. C. Hsu and J. G. Reynolds, Statistical Analysis of an Inter-laboratory Comparison of Small-Scale Safety and Thermal Testing of RDX, *Propellants Explos. Pyrotech*., 2014, accepted for publication.

Received: ((will be filled in by the editorial staff))
Revised: ((will be filled in by the editorial staff))

This manuscript was published in Propellant, Explosives and Pyrotechnics, **2015**, *40*, 583-589.

Disclaimer

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.